Available online at www.sciencedirect.com
SciVerse ScienceDirect
ELSEVIER
Procedia CIRP 5 (2013) 286 – 289
www.elsevier.com/locate/procedia

The First CIRP Conference on Biomanufacturing

HIFU positioning robot for less-invasive fetal treatment

Ken Masamune[a]*, Ichiro Kurima[a],
Kenta Kuwana[b], Hiromasa Yamashita[c], Toshio Chiba[c] and Takeyoshi Dohi[b]

[a]*Graduate School of IST, The University of Tokyo, 7-3-1 Hongo Bunkyo-ku, Tokyo 113-8656, Japan*
[b]*School of Engineering,Tokyo Denki University, 5 Asahi-cho, Senju, Adachi-ku, Tokyo 120-8551, Japan*
[c]*Clinical Research Center, NCCHD, 2-10-1 Okura, Setagaya-ku, Tokyo 157-8535, Japan*
* Corresponding author. Tel.:+81-3-5841-6370; *mail masa@i.u-tokyo.ac.jp*

Abstract

Fetus sacrococcygeal teratoma is a fatal disease which makes blood flow abnormal. Popular approach for this treatment is to cut the teratoma off, nonetheless it is high-invasive with risks. So the use of HIFU(High Intensity focused ultrasound) is now attracting attention because of its capability of burning vessels to stop blood flow without opening the uterine wall. For precise HIFU treatment, HIFU transducer is required to have movable focus point under the guidance of 3D-ultrasound image, and to have more rough movable area to find the target in real time. In this paper, we present a newly developed HIFU positioning robot which holds a HIFU transducer and the US probe. Initial evaluation test of positioning accuracy was performed and high precise positioning was achieved.

Selection and/or peer-review under responsibility of Professor Mamoru Mitsuishi and Professor Paulo Bartolo

Keywords: HIFU treatment, medical robot, link mechanism

1. Introduction

Fetus sacrococcygeal teratoma is a fatal disease [1]. Huge tumor grows at the lower back of the fetus, where blood flow is concentrated inside, and the treatment of removing the tumor is a high risk procedure. At present, popular approach for this treatment is to cut the teratoma off, however it is considered high-invasive with risks of caesarotomy and sometimes other important tissues including placenta in the uterine cavity are injured during the procedure. To solve this problem, the use of HIFU (High Intensity Focused Ultrasound) is attracting much attention because it has a high capability of burning vessels to stop blood flow without opening the uterine wall, in order to stop the growth of the tumor. (Fig. 1).

HIFU has been already used in clinical treatment such as prostate cancer, uterine fibroids, and so on [2-4]. However, in case of applying prenatal sacrococcygeal teratoma, the HIFU power transmission control becomes more difficult because the target tumor vessels are moved by floating in the uterine and by mother's breathing, and also there are important organs in the surrounding area of the target vessel.

Thus for precise HIFU treatment, HIFU transducer with 3D-ultrasound probe (shown in Fig. 2) is required for having a movable focus point, and also having more rough moving to find target. We developed the 1st prototype of HIFU positioning robot shown in Fig. 3. It has a 4DOF movement mechanism and can hold a phased array HIFU transducer with a 3D ultrasound probe for target observation.

In this paper, we developed a new HIFU positioning robot with new mechanism which holds HIFU transducer and the US probe as shown in Fig. 2. A tilting angle is added to extend the approach path of the HIFU transmission safely.

2212-8271© 2013 The Authors. Published by Elsevier B.V. Open access under CC BY-NC-ND license.
Selection and/or peer-review under responsibility of Professor Mamoru Mitsuishi and Professor Paulo Bartolo
doi:10.1016/j.procir.2013.01.056

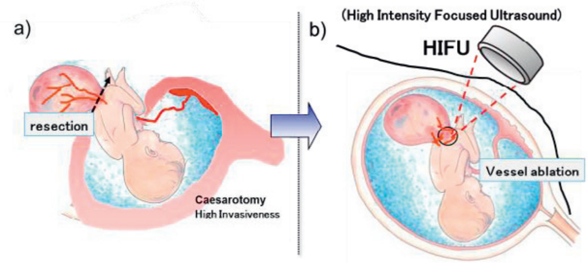

Fig.1 Innovation of treatment with HIFU (a) conventional open surgery, b) treatment using HIFU without open surgery)

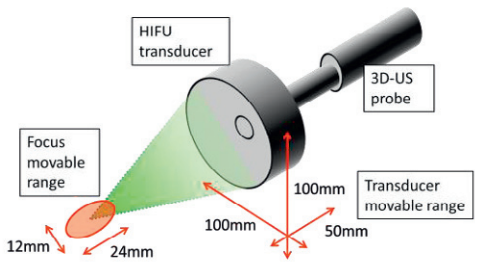

Fig.2 The assemblage of the 3D-US transducer and HIFUprobe

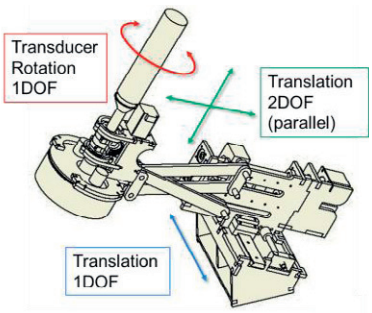

Fig.3 The 1st prototype robot

2. Mechanism of the robot

2.1. The prototype robot and the improvement points

The prototype robot was already developed and the basic performances are evaluated in the previous study [5]. Its features are as follows:

1. The robot has totally 3 axis for translation: one translation axis and two translation axis with parallel link mechanism.
2. One rotation axis are attached on the tip of the link for the US probe. Though the US probe can take 3D image, the resolution of the image is not isotropic and the rotation is needed to acquire better imaging during the HIFU targeting.
3. Operating range is 100mm × 100mm area on the contact surface of the abdomen, and 50mm depth.
4. Maximum speed of the tip is 10mm/s at most for each axis.
5. Positioning accuracy is less than 1mm, which is the same with the resolution of US images.
6. Compact, light weighted design compared to other HIFU positioning system.
7. Actuators are settled far from the body, though it's needless to sterilize the robot. It becomes easier to detach the HIFU transducer from the robot.

From the evaluation result, we designed the second prototype of the robot. The main improvement points are as follows:

1) **Positioning accuracy with considering the load on the tip**.
In use, at the distal end of this mechanism, the force from the water bag and the cable connected to the probe and the HIFU transducer for transmitting an ultrasonic wave is applied. The force will be always changed corresponding to the pose of the robot, the accuracy must be constantly maintained under conditions of expected accuracy. In the 1st prototype robot, we confirm its enough rigidity, however, the displacement error caused by lateral force is over 1mm. This backlash was derived from low rigidity of the links, and it can be reduced by increasing the thickness of the links.
2) **Additional DOF** is applied to acquire wider approach to the target. Especially adding the tilting mechanism of the HIFU transducer is needed.
In order to realize easy setting of the initial position, one more DOF is needed for adjusting the height and the tilting angle of the HIFU transducer.
3) **Feasible design.** Redesigning is needed for feasibility, installation and assembly easier. In particular for installation of the probe, we focus on reducing the number of assembly steps.

Based on the above points, we designed the second prototype robot described in the following section.

2.2. The second prototype robot design

There are several ways to add a tilting angle movement of the HIFU transducer. Considering the load to the distal end of the link, we added another link mechanism to rotate the transducer. The merit of using links is its compactness and its moving area which is mechanically restricted to avoid unintended movement. Fig. 4 shows the link mechanism of the robot.

The same mechanism with the 1st prototype (in Fig. 3) is applied for translating axis. Between two bottom links, one linear guide and links are added for rotation axis. In order to increase the total drive range, these actuators are set in the vertical direction. A parallel link is added in this translation axis and the initial position of the tip link is changeable by adjusting the node of the parallel link.

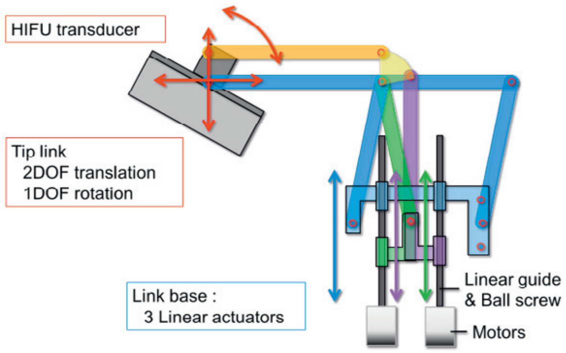

Fig.4 Link mechanism of 2nd prototype robot

The overview of the developed robot is shown in Fig. 5. The HIFU transducer (without the ultrasound probe) is mounted on the tip link. This robot will be attached to the bedside rail.

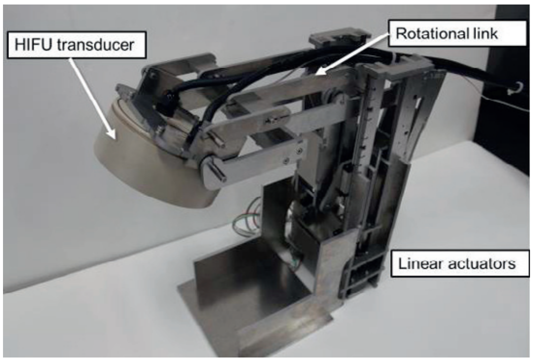

Fig. 5 Overview of the robot with HIFU transducer (without US probe)

3. System configuration

Fig. 6 shows the system configuration of HIFU robot. It comprises a 3D-US probe, US imaging system, the HIFU transducer with its control system, the robot and its device control system using PIC. The position information are transferred via USB communication and integrated in the graphic workstation which has a customized image visualization software, robot control software and HIFU irradiation control program.

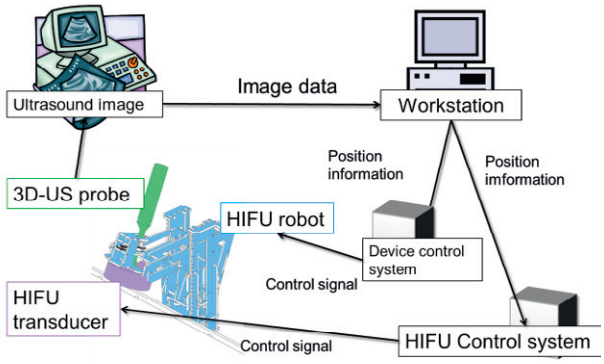

Fig. 6 System configuration of the HIFU robot system

By using this system, we can perform observing the ultrasound imaging real timely and put/track the target and transmit the power to the focal point consecutively. Image feedback control system for HIFU is already researched in e.g. [6][7], and they realized the semi or automatic detecting and tracking of the target region unless the target is appeared in the US image. Besides, our HIFU transducer is based on the basic research development in [8] and a multi phased array are distributed in the hemisphere, so the focal point are movable within the region of about 20mm cube. Thus we're considering that the combination with the multi-phased array HIFU and this robot will increase efficiency of the procedure.

4. Experiments of the positioning of the robot

4.1. Experimental setup

Positioning accuracy of this robot was evaluated. Fig. 7 shows the experimental setup of each axis. A reference marker by 3D measurement system (Polaris™, NDI, Canada) are used to measure the tip transducer's position (Mockup metal material of 1.5Kg mounted on the tip). From the initial point of the robot (at the original point), designated values are sent to the robot. Then the robot is moved to each lattice node points. We measure the 3D position of the tip by 3D measurement system. The coordinate system between the evaluation lattice (Fig.7 left) and 3D position measurement sensor space was calibrated in advance. The affine coordinate transformation are used for calibration and calculation of each points. The displacement errors between the theoretical lattice nodes and the measured points are calculated. The number of the trial is 5 times.

4.2. Result of the positioning accuracy

Total average of the positioning accuracy error for each axis is shown in Table 1. Each error results in quite good performance despite the use of 3D measurement device which has inherent RMS of 0.35mm. And more, the 1.5Kg mock is mounted at the tip, there seem to be no influence for the positioning accuracy.

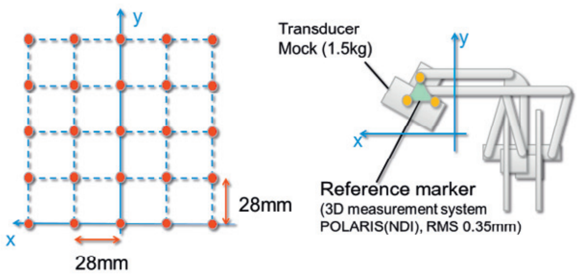

Fig.7 Evaluation setup for positioning accuracy

Table 1. Positioning accuracy error

Axis	Average error [mm] (N=5)
x	-0.2±0.3
y	-0.1±0.1
z	-0.0±0.1

5. Discussion and Conclusion

In this paper, our 1st and the 2nd prototype of HIFU positioning robot are presented. A newly designed 4DOF mechanism is developed to hold a phased array HIFU transducer with a 3D ultrasound probe for target observation. Using this system, the surgeon is able to put the target on the image, and the robot can track the target position and transmit the power to coagulate the target region. The HIFU transducer will perform precise targeting by using phased array system. So, once the target region is moved outside of the focusing area, the robot can perform a large movement. It is a kind of hybrid control and we plan to optimize the controller in future research.

The movable region of the tip position is restricted by rigid link system in this robot, so the risk of interfering with the patient is reduced and the robot would not harm the patient by unintended movement. One of the clinical concern is the use of water bag, which should be set between the HIFU transducer and the patient. For more strict feasibility experiment and clinical application, a suitable design of the water bag is needed.

At present, evaluations on this hybrid positioning are not tested, because the HIFU transducer itself requires more precise evaluation including quality and effectiveness of the treatment in-vivo. Especially, because of ultrasound's refraction in the tissue on the way to target, the image is distorted resulting in displacement of the coordinate system and the robot. So we consider to move robot not in absolute coordinate but in relative coordinate system. We will perform the total evaluation of the whole system in the next step.

In this paper, we present a newly developed HIFU positioning robot which holds a HIFU transducer and the US probe. We conclude that the initial evaluation test of the 2nd prototype robot was performed and high precise positioning was achieved in the experimental settings.

Acknowledgements

This research is partly supported by Health Labour Sciences Research Grant. The HIFU transducer will be provided by one of the research project member, Prof. Umemura, Tohoku University, Japan, and we like to express gratitude in this place for his laboratory.

References

[1] Alan W. Flake, Michael R. Harrison, N. Scott Adzick, Jean-Martin Laberge, Steven L. Warsof, Fetal sacrococcygeal teratoma, Journal of Pediatric Surgery, Volume 21, Issue 7, July 1986, Pages 563-566

[2] Davies, BrianL., et al., A robotic approach to HIFU based neurosurgery, 1998, Medical Image Computing and Computer-Assisted Intervention — MICCAI'98, 1496, pp.386-396

[3] Hiromasa Yamashita, et al., 2009. Automatic Delivery system of high Intesity Focused Ultrasound with Real-time 2D-Ultrasound Imaging analysis for Fetal Cardiac Intervention, The Society of Life Support Technology, Vol.21, No.4, pp.172-179

[4] Koizumi N. et al., 2008, Feed-forward controller for the integrated non-invasive ultrasound diagnosis and treatment, J Robotics and Mechatronics, 20(1), pp.89-97

[5] Kurima I, et al.,2011, Positioning device of HIFU transducer for Minimally invasive Fetus Surgery, ABML 2011(Assistive Technology, Bio Medical Engineering and Life Support) 2011, O1-6, Tokyo, Nov. 3-5, 2011.

[6] Casper, A.; Dalong Liu; Ebbini, E.S.; , 2012, "Realtime Control of Multiple-focus Phased Array Heating Patterns Based on Noninvasive Ultrasound Thermography," Biomedical Engineering, IEEE Transactions on , vol.59, no.1, pp.95-105

[7] Umemura, S.; Cain, C.A.; , "Acoustical evaluation of a prototype sector-vortex phased-array applicator," Ultrasonics, Ferroelectrics and Frequency Control, IEEE Transactions on , vol.39, no.1, pp.32-38, Jan. 1992